DE-FC26-03NT41448

GE Power Systems

Enabling & Information Technology To Increase RAM for Advanced Powerplants

Technical Progress Report

For Semi-Annual Period
Beginning March 1, 2003
Ending August 31, 2003

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National Energy Technology Laboratory
Morgantown, WV 26507-0880

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DISCLAIMER

ABSTRACT

The project will develop, validate and accelerate the commercial use of enabling technologies for coal/IGCC powerplant condition assessment and condition based maintenance. The purpose of condition assessment is the realtime automatic extraction of useful information from operating data to guide decisions, which differentiates it from traditional powerplant monitoring. By contrast, condition based maintenance relies upon the use of this derived information to accurately predict capital parts consumption and maintenance outage schedules. This report summarizes the work accomplished in the March 1, 2003 to August 31, 2003 and includes progress details from each of the four Tasks.

Task 1- Hot Gas Path Parts Life Prediction: generates material properties data to enable combustor and hot gas path parts life prediction methodologies for coal/IGCC power plants. The report includes the status of material selection, test data requirements, acquiring field hardware evaluations, and preliminary analysis considerations for the reporting period.

Task 2 - Powerplant In-Service Health Monitoring: demonstrates new technologies to determine the in-service health of advanced technology coal/IGCC powerplants. The report includes a definition of the sensor requirements, initial sensor capability studies, and the status of IR pyrometer development. Sensors were identified, ranked, and prioritized; the need for further development was assessed; and sensor functional specifications were generated.

Task 3 – Advanced Methods for Combustion Monitoring and Control: develops and validates advanced monitoring and control methods for coal/IGCC gas turbine combustion systems. Combustion control objectives have been identified, including overall operability and performance metrics. Combustion dynamics modeling is a high-priority focus due to its importance in the current gas turbine fleet.

Task 4 - Information Technology (IT) Integration: demonstrates IT tools for advanced technology coal/IGCC powerplant condition assessment and condition based maintenance. The new technologies developed in Tasks 1, 2, and 3 will be integrated with new and existing IT platforms. These IT platforms will serve two fundamental purposes: 1) to automatically extract useful information from operating data to guide decisions and 2) to use the derived information to predict capital parts consumption and maintenance outage schedules. This report includes status on development of the GateCycle™ software to model complete-plant IGCC systems, as well as the Universal On-Site Monitor (UOSM) to collect and integrate data from multiple condition monitoring applications at a power plant.

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Introduction

Enabling & Information Technology To Increase RAM for Advanced Powerplants

Objective:

Advanced analytical part lifing models, advanced sensors and controls, and highly integrated information technology (IT) platforms will be demonstrated in merchant coal/IGCC (Integrated Gasification Combined Cycle) gas turbine combined cycle powerplants located in the United States. The new technologies will be used to optimize the performance and life cycle cost of the power generation assets on a real-time basis, including the effects of power demand and ambient conditions. The key success metrics will be increased powerplant reliability, availability and maintainability (RAM), performance (e.g. output and efficiency), and operability; as well as significantly reduced pollutants.

Background:

The project will develop, validate and accelerate the commercial use of enabling technologies for powerplant Condition Assessment and Condition Based Maintenance. The purpose of Condition Assessment is the real-time, automatic extraction of useful information from operating data to guide decisions, which differentiates it from traditional powerplant monitoring. By contrast, Condition Based Maintenance relies upon the use of derived information to accurately predict capital parts consumption and maintenance outage schedules.

Relevancy:

Significant benefits to the U.S. public will be additional electricity delivered to the power grid, with fewer interruptions, particularly during periods of peak demand; and reduced generation cost resulting from lower equipment maintenance costs, lower insurance premiums, more stable and reliable power transmission and distribution, and shorter learning curves when new power generation technologies are introduced to the market. Additional benefits include significant reduction in pollutants and improved capability for burning a wide variety of gaseous and liquid fuels in advanced power plants.

Period of Performance: March 01, 2003 to February 28, 2008

Executive Summary

The Enabling & Information Technology To Increase RAM for Advanced Powerplants project will develop, validate and accelerate the commercial use of enabling technologies for coal/IGCC powerplant condition assessment and condition based maintenance. The purpose of condition assessment is the realtime automatic extraction of useful information from operating data to guide decisions, which differentiates it from traditional powerplant monitoring. By contrast, condition based maintenance relies upon the use of this derived information to accurately predict cap ital parts consumption and maintenance outage schedules. This report summarizes the work accomplished in the March 1, 2003 to August 31, 2003 and includes progress details from each of the four Tasks.

Task 1- Hot Gas Path Parts Life Prediction: generates material properties data to enable combustor and hot gas path parts life prediction methodologies for coal/IGCC power plants. The report includes the status of material selection, test data requirements, acquiring field hardware evaluations, and preliminary analysis considerations for the reporting period.

Task 2 - Powerplant In-Service Health Monitoring: demonstrates new technologies to determine the in-service health of advanced technology coal/IGCC powerplants. The report includes a definition of the sensor requirements, initial sensor capability studies, and the status of IR pyrometer development. Substantial progress has been made during the first sixth months of the program. Sensors were identified, ranked, and prioritized; the need for further development was assessed; and sensor functional specifications were generated. Under the IR Pyrometer task (sub-task 2.3), the thermal variation of two sets of stage 1 turbine buckets was characterized before the parts were installed in the MS7001FA+e gas turbines at the Duke Maine Independence powerplant. The team installed, calibrated, and determined the Line-of-Sight (LOS) of the pyrometers in these gas turbines and obtained temperature data during operations. Absolute temperature and emissivity was measured using spectroscopy in one of these gas turbines. The methodology of predicting temperature of the buckets is being improved using updated analysis tools, and a methodology to determine and report the condition of the buckets in real time is being developed.

Task 3 – Advanced Methods for Combustion Process Modeling: develops and validates advanced monitoring and control methods for coal/IGCC gas turbine combustion systems. Combustion control objectives have been identified, including overall operability and performance metrics. Combustor operability is determined primarily through constraints set by levels of combustion dynamics, pollutant emissions, lean blowout, and flame flashback. Model-based control architectures will require a representation of each of these processes. Appropriate physics-based model formulations to describe each of these constraints are being identified. Combustion dynamics modeling is a high-priority focus due to its importance in the current gas turbine fleet. An existing combustion dynamics prediction tool has been evaluated and is being modified for use as a component of a model-based controller. A single nozzle combustion facility is being prepared to provide data for model comparison and system identification experiments. Fuel quality requirements for IGCC-based gas turbines are being reviewed. IGCC combustor control development is being coordinated with the GE program manager of the DOE-sponsored Fuel-Flexible Combustor Program.

Task 4 – Information Technology (IT) Integration: demonstrates IT tools for advanced technology coal/IGCC powerplant condition assessment and condition based maintenance. The new technologies developed in Tasks 1, 2, and 3 will be integrated with new and existing IT platforms. These IT platforms will serve two fundamental purposes: 1) to automatically extract useful information from operating data to guide decisions and 2) to use the derived information to predict capital parts consumption and maintenance outage schedules. This report includes status on development of the GateCycle™ software to model complete-plant IGCC systems (sub-task 4.1), as well as the Universal On-Site Monitor (UOSM) to collect and integrate data from multiple condition monitoring applications at a power plant (sub-tasks 4.2, 4.3).

The functionality of GE's GateCycle™ commercial heat-balance simulation software is being extended in order to model complete coal/IGCC power plants. This extended GateCycle™ software will be used to build and configure the on-line EfficiencyMap™ performance monitoring software system at a selected coal/IGCC site. The first key task was to rework the database foundation so that the IGCC extensions could be added. The current database system used in GateCycle is not able to support the substantial extensions needed to support IGCC modeling, so an industry-standard SQL database architecture was selected. Several different SQL database design alternatives were explored and tested, with speed of access being the primary issue that needed to be resolved. By focusing on improved stored procedure implementations, a design of a GateCycle SQL database version was completed and coded, and initial testing has shown it to be acceptably fast for a commercial-grade release.

Requirements gathering and preliminary design work have begun for the database and analysis extensions needed to support IGCC modeling. These key enhancements include:

- GateCycle stream data structures must be extended to increase the number of constituents supported in a gas stream (the current limit is 11 constituents)
- Database and property calculation routines must be added for solid streams
- Database and property calculation routines must be added for mixed-phase streams (gas/solid, gas/liquid and liquid/solid)
- Current GateCycle unit operation models for gasifiers and gas saturators will be enhanced
- Unit operation models will be added for syngas coolers, solid and slurry handling equipment, distillation/absorption columns and gas cleanup equipment
- Core convergence and analysis routines will need to be extended and tested for the more complex chemical system and plant integration inherent in IGCC systems

The UOSM hardware and GE-ICAS2002 condition monitoring system have been installed at the initial MS7001FA+e test site. This system utilizes approximately 50 separate software applications and rules. Synergy software was developed by GE-FANUC to monitor and integrate program anomaly outputs. The system will continue to be improved and upgraded as new applications and rules are developed. Two site installations are being planned in this program: one at Duke Fayette, and the other at TECO Polk. The latter is a coal/IGCC powerplant.

Experimental

This section presents a descriptive summary of the experimental methods in use for the conduct of this project. Described below are the experimental methods being used for the research efforts by Task, and where appropriate Sub-task, during this reporting period. Not all sub-tasks have yet been initiated during this first six months of the program.

Task 1: Combustor and Hot Gas Path Parts Life Prediction

Experimentation has not started for Task 1, however material selection, test planning, purchase of material, and preliminary specimen analysis are under way with experimentation planned to begin in 2004. The planned experiments will include tensile, low cycle fatigue (including hold time), fracture toughness, creep, thermo-mechanical fatigue, torsional low cycle fatigue, fatigue crack growth, and creep-fatigue interactions. Additionally, coating effects will be evaluated along with microstructural evaluation of specimens and field hardware. The testing is to be accomplished at accredited test laboratories, including Georgia Tech and GRC. ASTM standards for mechanical testing are to be observed.

Task 2: Powerplant In-Service Health Monitoring

Most of the activities in Task 2 are still in the planning stages. Experimental work has begun in subtask 2.3, as reported below.

Subtask 2.3 - IR Pyrometer for Condition Based Maintenance

Infrared (IR) Pyrometry of stage-one turbine buckets is being developed for Condition Based Maintenance (CBM) predictions. This has been an on-going effort at GE over several years. During the last six months to advance this effort, the tasks were focused around the following:

1. Pre-determining the thermal variation of the buckets
2. Pyrometer alignment at the Duke Maine Independence plant
3. Reducing the effect of lens fogging on pyrometer measurements
4. Determining absolute temperature and emissivity using spectroscopy
5. Improving the methodology to predict temperature of the buckets
6. Developing a methodology to determine condition of the buckets
7. Developing a strategy for bucket reliability management

Pre-determining the Thermal Variation of the Buckets

The methodology involves placing individual buckets on a flow check stand, heating them to an elevated temperature, then inducing a transient cooling period by supplying internal cooling air to the bucket, over which time the part is thermally imaged with an Infrared (IR) camera to capture the external surface temperature. The measurement apparatus is shown in Fig. 2.1 Analysis of the data is done per the method described in Ref. 1.

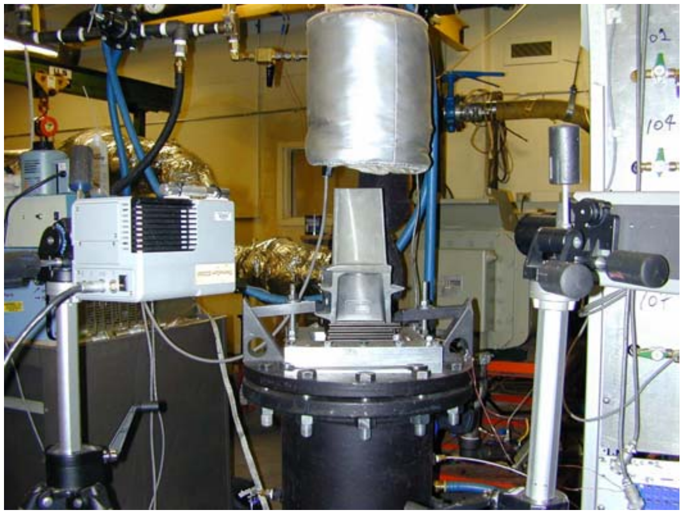


Figure 2.1: Plenum flow chamber with bucket affixed to the top

<u>Pyrometer Alignment at the Duke Maine Independence Plant</u>
The fiber-optic cables for both GT-1 and GT-2 were replaced during an outage in March-April, 2003. Calibration checks of both cables and units where performed both before and after cable replacement (Figures 2.2, 2.3). The calibration of the detector electronics was then adjusted after replacement. Modifications to improve the LOS were also done, shown in Fig. 2.4. The turbine modification included modified S1 retaining ring, new manway cover and new sight tube.

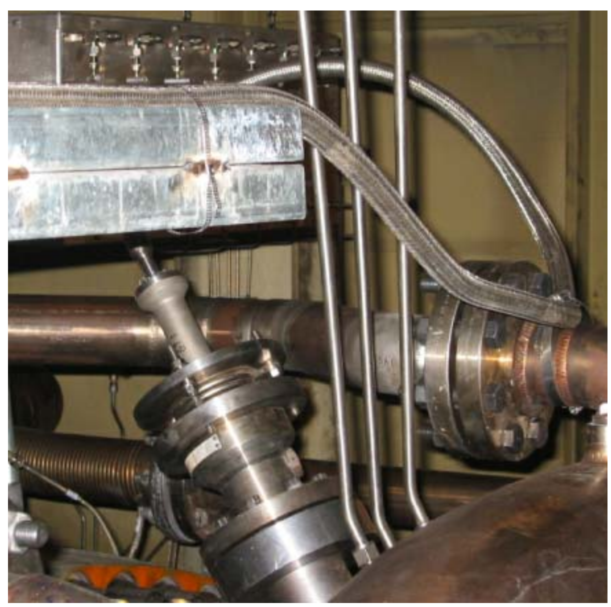


Figure 2.2 (left): Alignment flange positioned on black body furnace during calibration
Figure 2.3 (right): Optical fiber and alignment flange installed on turbine

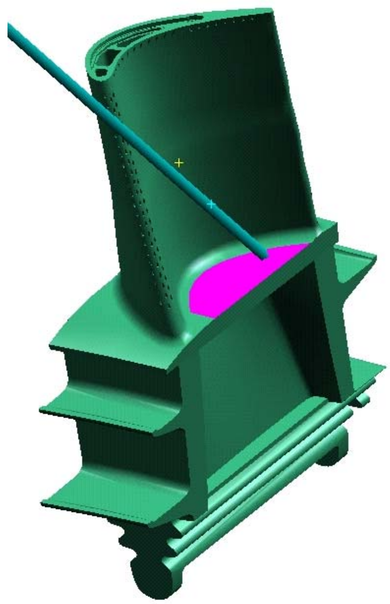


Figure 2.4: Modified LOS for Duke MI site

Reducing the Effect of Lens Fogging on Pyrometer Measurements

Fogging of the pyrometer optical system during on-line operation causes an error. The fogging error was historically measured during the pyrometer maintenance. The measurement setup is shown in Figure 2.5.

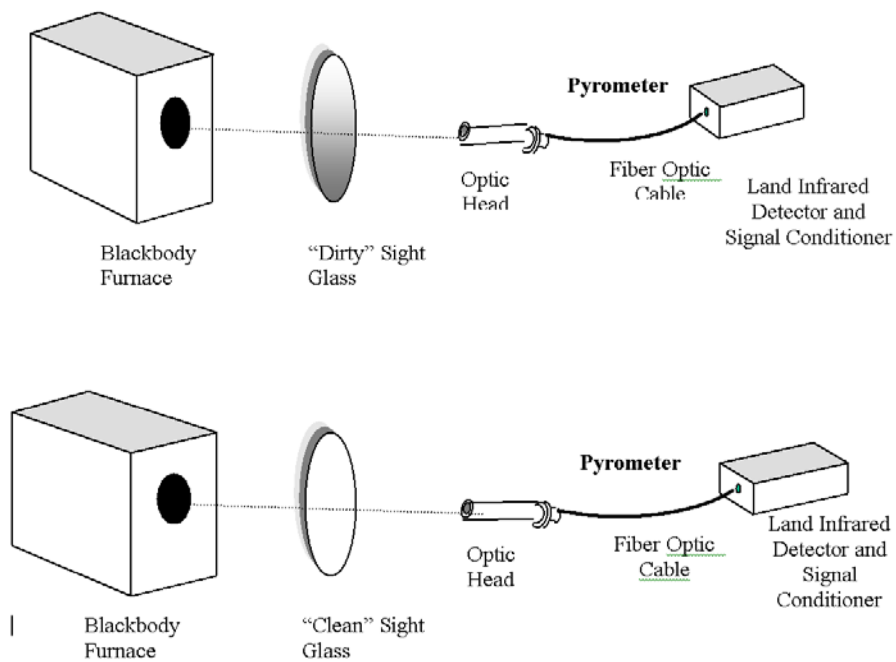


Figure 2.5: Fogging error measurement setup

To quantify the error and compensate for it, all data was compiled in a table with fired hours associated with a measured error. A transfer function between the fogging error and fired hours was then developed (Fig. 2.6). Together with regular optical system cleaning at each shutdown, the transfer function will be used to correct the error between maintenances.

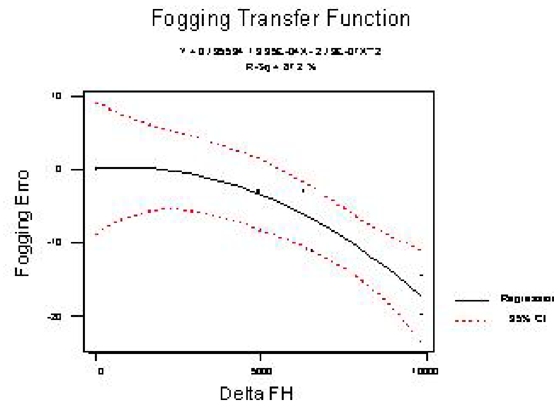


Figure 2.6: Fogging error transfer function

<u>Determining Absolute Temperature and Emissivity using Spectroscopy</u>
At the Duke Maine Independence Power Station, there are Land single wavelength pyrometers installed on both 7FA+e gas turbines (GT-1 and GT-2). These Land pyrometers return a calibrated high speed radiance signal to a data acquisition system. Thus we are able to obtain a radiance profile of each bucket along a single line of site. However, the conversion from radiance to temperature assumes that the emissivity of the buckets is 1.0. This is not the case in reality, which leads to an offset in absolute value. Outlined here is a method to determine absolute temperature without *a priori* knowing the emissivity of the buckets.

The IR radiance (R) emitted by the first stage buckets (and indeed any hot object) is given by the Plank relation:

$$R = \frac{\varepsilon\, C_1}{\lambda^5} \frac{1}{\exp\left[C_2 / \lambda T \right] - 1} \approx \frac{\varepsilon\, C_1}{\lambda^5} \frac{1}{\exp\left[C_2 / \lambda T \right]}$$

where ε is emissivity, λ is wavelength, T is temperature, and C1 and C2 are the first and second optical constants equal to 3.74e8 and 1.44e4 respectively. The Land pyrometer measures radiance at a fixed wavelength (~1um). To determine an accurate temperature, the emissivity of the bucket must be known. By measuring a spectrum from the buckets we obtain radiance as a function of wavelength. If this spectra is fit to the Plank relation, the emissivity is an irrelevant scaling factor. However, it should be noted that this is true if it is assumed that the emissivity is a constant spatially on the bucket and a constant with temperature. In the case of the 7FA+e buckets, both of these are reasonable assumptions, thus it is possible to obtain a temperature from the fitted spectra.

There are several factors involved that complicate the conversion from theory to experimental reality. First, the spectrometer is not able to collect data at the high speed rate of the Land pyrometer. To obtain good statistics, a scan length of several seconds is required. Given the GT is spinning at 3600 RPM, the radiance we measure is an average of that emitted by all the buckets. Thus it is only possible to obtain an average temperature for the wheel. The second factor has to do with the fact that there is a temperature gradient across the buckets. Each point that is at a different temperature is emitting a different Planck curve. A sum of Planck curves is not equal to a Planck curve. However, in the analysis this is ignored. Investigation of the errors associated with ignoring this indicates an error of 0.2%.

Improving the Methodology to Predict Temperature of the Buckets

The pyrometer field of view is small compared with the total surface area of the gas turbine buckets. In order to extend the real time temperature measurements to the entire bucket, a UniGraphics LOS utility is being developed to rapidly transfer the pyrometer measurements to an Ansys finite element model of the bucket. The flow chart of the utility illustrated in Figure 2.7.

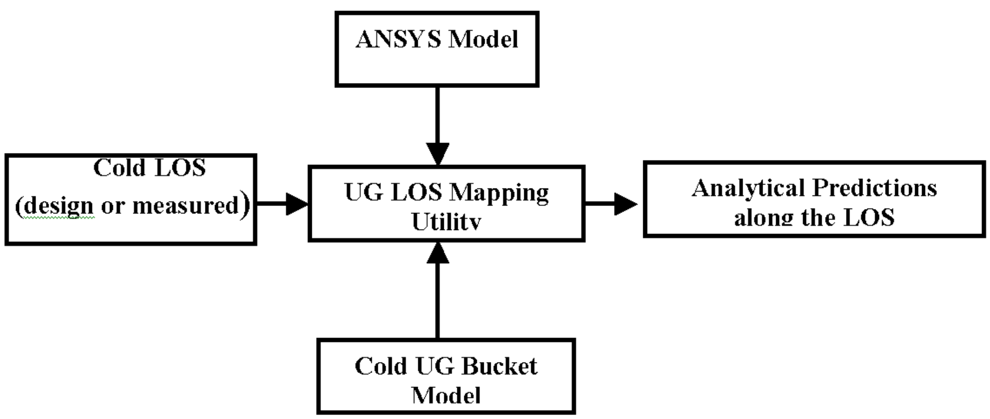


Figure 2.7: UG utility flow chart

The quality of the temperature validation is highly dependent on the reliability and fidelity of the analytical models developed to support the surface temperature predictions. Therefore, the initial focus of this effort will be to update the aerodynamic, heat transfer, thermo-mechanical models used to validate the original design configuration.

Developing a Methodology to Determine Condition of the Buckets

A transfer function between the mean bucket temperature measured by the pyrometer and the gas turbine firing temperature is being developed. This transfer function will be used to adjust the predicted bucket life as a function of firing temperature and fired hours, under a wide range of load conditions.

Developing a Strategy for Bucket Reliability Management

A strategy for identifying bucket abnormalities is being developed, as illustrated in Figure 2.8.

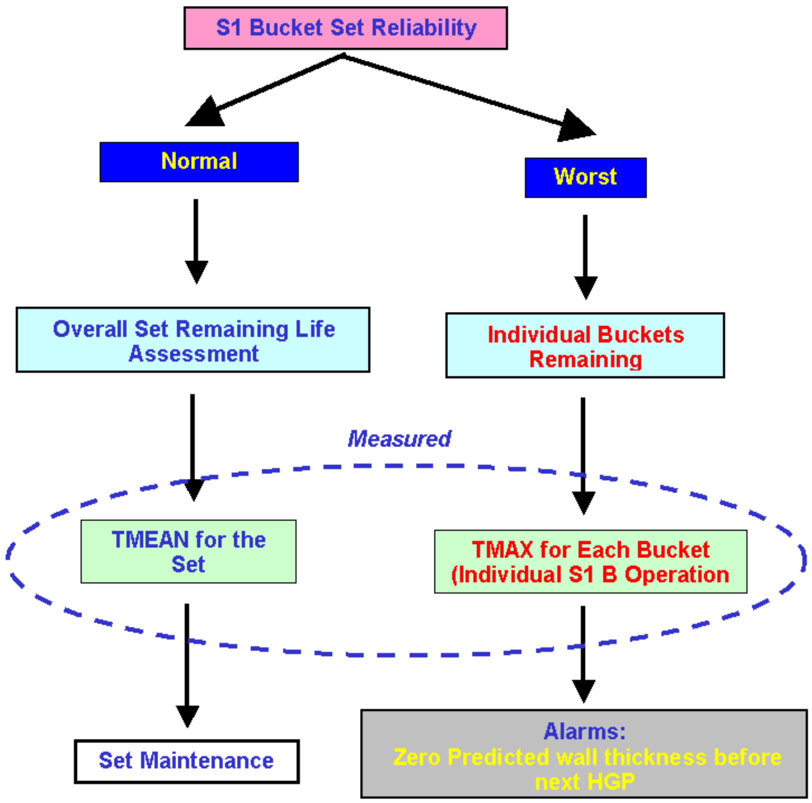


Figure 2.8: Flow chart of the bucket reliability management using pyrometer measurement

Task 3: Advanced Methods for Combustion Monitoring and Control

The focus of Task 3 for this reporting period has been on the development of physics-based models to describe various aspects of the combustion process in an industrial gas turbine. The models will be used to guide control system design for improving the operability and durability of the combustion system. Several physical models will be developed during the program including those describing pollutant emissions, combustion stability (lean blowout and flashback), and combustion dynamics.

Work during this reporting period has been focused on developing models for combustion dynamics. The model development process consists of both analytical and experimental components. An analytical framework is devised using fundamental conservation laws and from this a model is synthesized. In the case of combustion dynamics in a gas turbine, several simplifying assumptions must be made to render a tractable set of equations. The simplified model is then subjected to experimental validation. The following section describes the experimental techniques used to acquire data for model validation. Comparison of validation data with model predictions is shown in the results and discussion section below.

Experimental Apparatus

Experiments were performed using an existing laboratory-scale combustor. The combustor scale makes it suitable for testing individual nozzles from a multi-nozzle can combustion system. The experimental device is traditionally used for dry low-NOx (DLN) nozzle development. The single-nozzle rig (SNR) was chosen for performing combustion dynamics validation and control experiments because it contains many design features relevant to full-scale can combustors and can be operated at a small fraction of the cost. Specific features relevant to full-scale combustors include reverse flow liner, similar flame stabilization characteristics, and ability to run under simulated full-load conditions of an F-class turbine.

Figure 3.1 shows a schematic diagram of the SNR combustor facility. Preheated air enters the combustor test section after passing through passages formed by a reverse flow baffle.

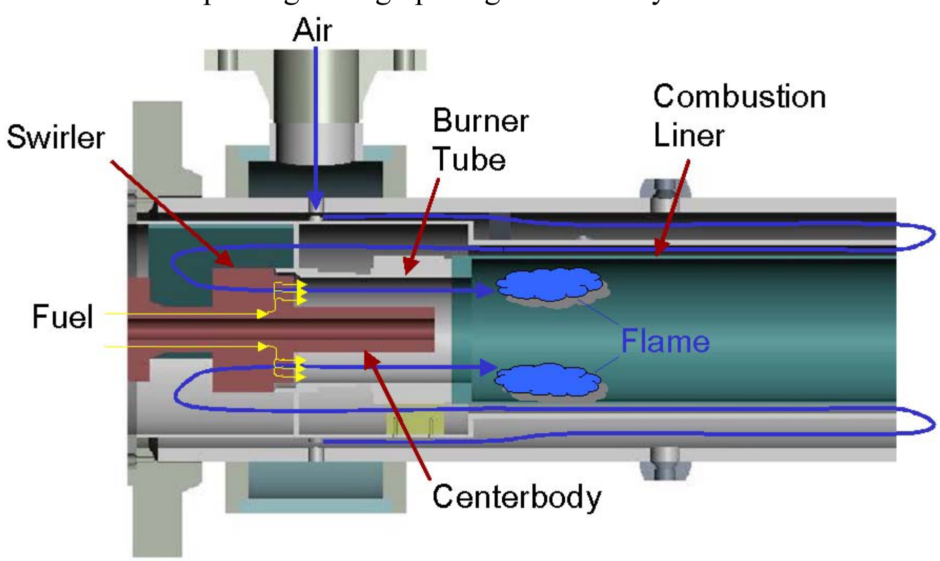


Figure 3.1: Schematic diagram of single-nozzle combustion rig

This airflow arrangement allows cooling of the combustion liner by the incoming primary combustion air without need for secondary cooling flow. After passing through the reverse flow passages, the air enters a plenum section before passing through a fuel premixer. The premixer consists of an annular flow passage with a set of swirl vanes to create vortical motion in the flow before it enters the combustor. Fuel is injected into the swirling flow through a set of faired fuel spokes protruding radially from the premixer centerbody (Fig. 3.2).

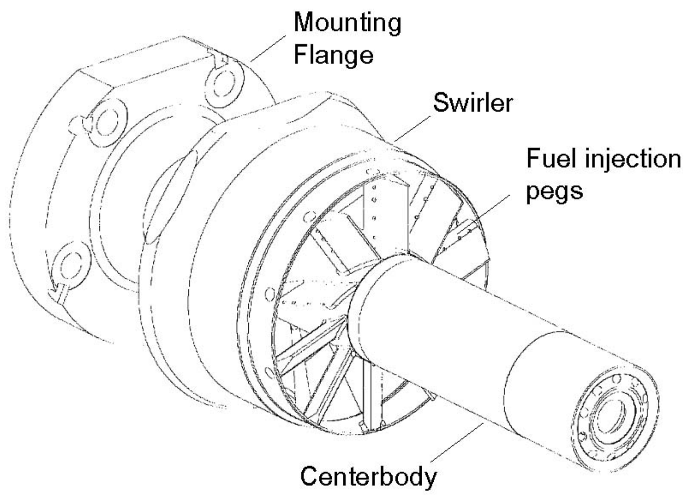


Figure 3.2: Fuel premixer used in single-nozzle experiments

The well-mixed fuel-air stream enters a combustion chamber with a sudden flow expansion near the upstream end to facilitate flame stabilization. Typical air and fuel flow rates for the facility are m_{air} = 3 to 5 lb_m/s and m_{fuel} = 0.1 to 0.17 lb_m/s, respectively. The air and fuel flows are measured with venturi flow meters. The air and fuel flow measurements uncertainties are typically 3 and 1.3 percent, respectively. The uncertainty in fuel-to-air ratio is typically 3 percent.

The SNR is fitted with several probes to detect pressure oscillations associated with combustion dynamics. The probes consist of fast response pressure transducers (PCB Model 102M43) coupled to sense tubes that protrude into various places inside the facility flow path. The sense tubes are ¼ in diameter stainless steel and are terminated with a long coil of copper tubing to suppress natural resonance in the frequency range where combustion dynamics typically occur (f > 1 Hz). The pressure probes were distributed along the flow path and combustion chamber to allow identification of resonant acoustic standing waves that are excited during combustion dynamics events.

Data from the experiments were acquired using two separate recording systems. Pressure, temperature and flow rate data were acquired using a PC-based data acquisition system. The data logging rate on this system is approximately 3 Hz has the capacity to read approximately 100 data channels at this rate. The fast response pressure transducer signals are recorded using a digital tape recorder with a bandwidth of 10 kHz.

The SNR facility and pressure measurement systems described in the preceding paragraphs were used to perform combustion experiments to determine the characteristics of thermo-acoustic instabilities (combustion dynamics) under various operating conditions. The data derived from these experiments were used to validate a combustion dynamics modeling tool. The dynamics modeling tool, the validation results and the control scheme to be developed later in the program are described in the following section.

Task 4: Information Technology (IT) Integration

Sub-Task 4.1 - Performance Modeling for Coal/IGCC Powerplants

To extend the GateCycle™ software to model complete IGCC power plants, it was necessary first to rework the database foundation in the code to enable the code to be restructured to eliminate the data structure limitations that were preventing major extensions from being made to the analysis and property calculations. The database system embedded in the current commercial release of GateCycle™ is based on EASE+, a commercial, proprietary flat-file binary database system that is no longer viable or supported. A SQL-based database system was selected as a more robust and extensible platform that would enable the code structures to be extended to support modeling of IGCC technologies. The SQL framework selected was Microsoft MSDE, since GateCycle™ is a Microsoft Windows™-based application, MSDE has no run-time license fees, and MSDE is upgradeable to an enterprise-level, multi-user database (Microsoft SQL Server).

During the current reporting period, the basic functionality of the SQL database for GateCycle has been completed and is in beta testing. In this first phase, the intent is to reproduce the current functionality of the EASE+ version of GateCycle, while at the same time making sure that the architecture and design framework will support the needed IGCC extensions. All of the basic database functionality is now in place in the MSDE version of GateCycle; that is, models can be created, run and saved. In addition, basic import and export functionality via XML has been implemented and is in testing. The primary remaining major development task needed to bring the new SQL database version to commercial grade is to add the ability to import existing GateCycle models (importing directly from the current EASE+ database system). This EASE+ import functionality is expected to be completed during the next reporting period.

Now that the basic SQL database functionality is in place, it is possible to extend the database structures in GateCycle to support the extensions needed for modeling of IGCC technologies, and work has already begun on gathering the requirements for these database extensions and making sure that the new SQL architecture can be extended to support them. Specifically, the GateCycle stream data structures need to be extended to increase the number of gaseous constituents supported (the limit in the current database implementation is 11 constituents in each gas stream), support must be added for solid streams, and mixed streams (gas/solid, gas/liquid and liquid/solid) need to be architected and implemented. Once the data structures are in place to support extended stream modeling, the property calculations and unit operation models can be designed and implemented.

Sub-Task 4.2 - Coal/IGCC Powerplant Data Integration

The Universal On-Site Monitor (UOSM) is being developed to collect and integrate data from multiple condition monitoring applications at a power plant: turbine-generator controls, plant distributed controls, emissions monitoring, etc. Pilot testing of USM hardware and software is in-progress in several GE development laboratories and pilot powerplants. The hardware is shown in Fig. 4.1.

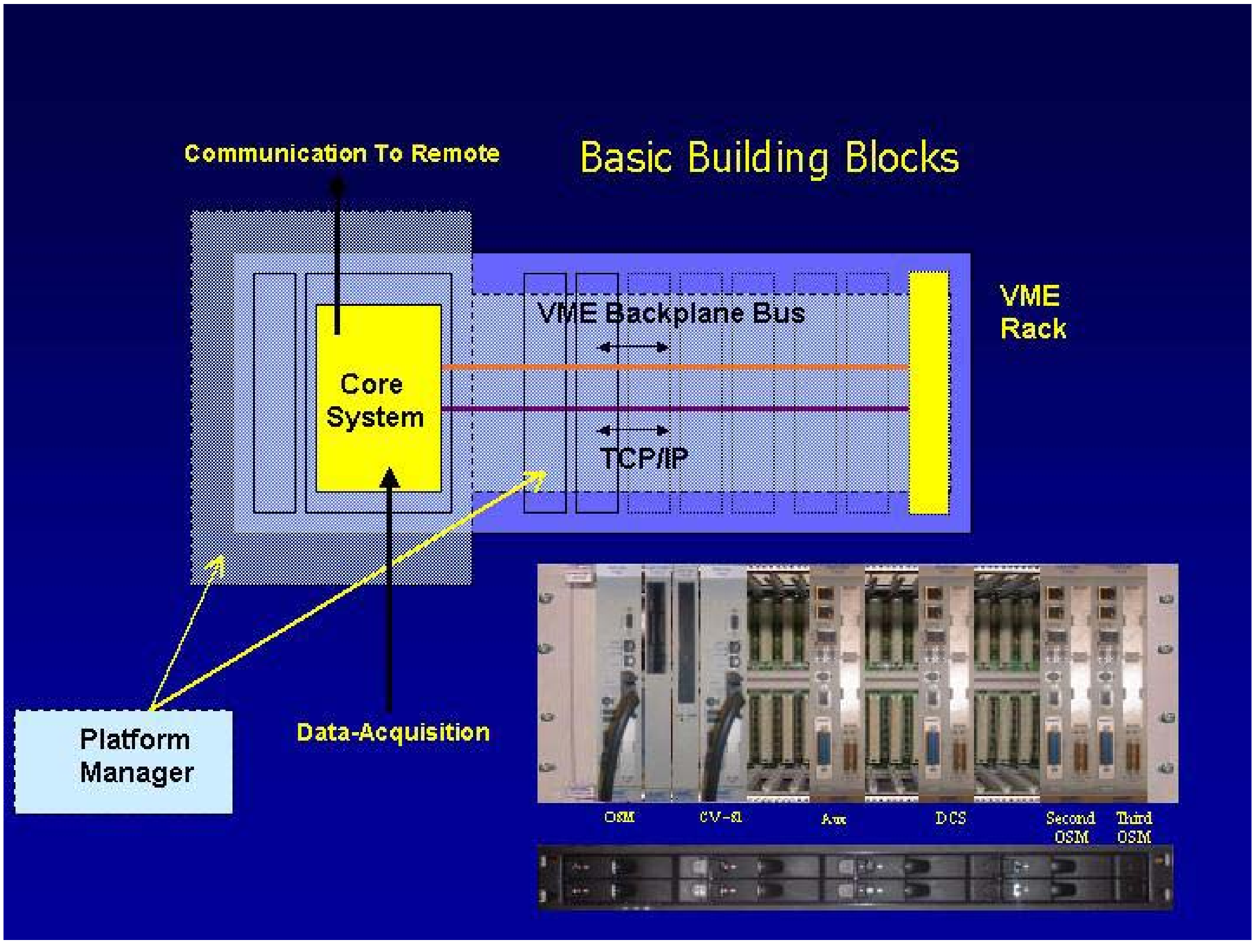


Figure 4.1: Universal On-Site Monitor hardware (typical)

Results and Discussion

The program status results are presented on a separate Task basis, as each of the four Tasks address separate areas of effort. Detailed task results are discussed for each active subtasks, as appropriate, for activities during this reporting period. An overview section has been included to clarify each task's (and sub-task's) intentions, and aid the understanding of progress to date.

Task 1 Status/Discussion:

Overview: This report details progress for Task 1, Combustor and Hot Gas Path Parts Life Prediction. The contributors to Task 1 are the GE Global Research Center, Georgia Tech University, GE Aircraft Engines, and GE Power Systems. Task 1 consists of 4 sub-tasks as follows:

> Sub-Task 1.1: Physics based Metallurgical Tool Development: The mechanical behavior of combustor and HGP materials under complex load / transient histories will be characterized for advanced coal/IGCC gas turbine parts. An investigation of the service history of selected gas turbine combustor and HGP parts will be performed to determine those parts that are not meeting design life and/or causing unscheduled maintenance of the gas turbine. Laboratory mechanical property testing will be conducted to characterize the material behavior under the mechanical/thermal/environmental conditions during gas turbine operation and to develop the analytical models in Task 1.2. . Parameters will be defined to mathematically correlate the microstructural state to residual mechanical properties and part life via transfer functions, which will be experimentally verified in Task 1.3.
>
> Sub-Task 1.2: Analytical Life Assessment Model Development: Improved constitutive equations of materials behavior will be developed based on the mechanical property data generated in Task 1.1. Lifing models that take into account complex material behavior interactions such as creep/fatigue, HCF/LCF, and hold time effects will be developed to replace the simple linear superposition models currently used today. In addition, improved fracture mechanics models will be studied to address damage tolerance in the lifing of fracture-critical parts.
>
> Sub-Task 1.3: Experimental Verification of Life Assessment Methodology: Transfer functions that correlate the metallurgical state of the materials (i.e. service/exposure history) to residual part life will be experimentally verified. The transfer functions will accurately represent changes in microstructure resulting from service exposure under conditions representative of the gas turbine operating environment, including transient and off-design conditions.
>
> Sub-Task 1.4: Field Validation of Life Assessment Methodology: Combustor and HGP parts will be removed from powerplants operated by DENA and extensively evaluated to validate the predicted part life. The parts will be evaluated using destructive and NDE techniques to determine microstructural changes, damage accumulation and/or failure modes in service. Residual mechanical properties will be measured. These data will

ensure that the models developed in Task 1.2 represent the true physics of the materials behavior.

Task 1 Discussion:

The sub-tasks are being initiated at different times. For the reporting period, sub-tasks 1.1 and 1.2 have been initiated. Inquiries regarding sub-task 1.4 have been made and plans will be finalized based on the availability times of field hardware. The scope and direction for sub-task 1.3 will be developed as sub-task 1.1 winds down and sub-task 1.2 moves to the forefront.

The schedule is as follows:

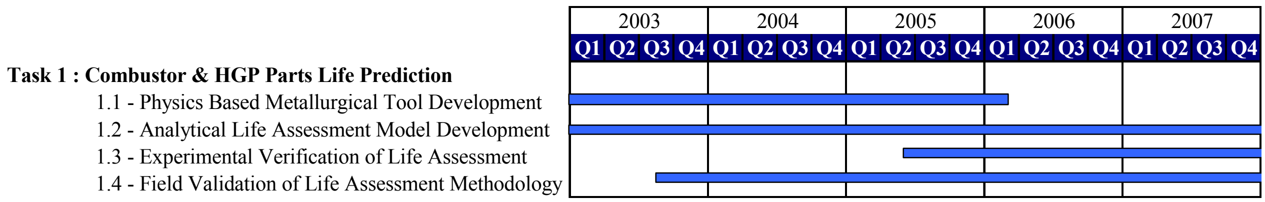


Figure 1.1: Task 1 Schedule

Work on Sub-Tasks 1.1, 1.2, and 1.4 has been initiated and continues. Details of progress to date are included below:

Sub-Task 1.1 - Physics based Metallurgical Tool Development

Georgia Tech, GRC, and GEPS are carrying out this sub-task. The first item to be discussed is the selection of materials. DS GTD-111 was selected as the Hot Gas Path alloy. In discussions, we decided to put a much greater emphasis on the HGP early in the project and then to start the Combustor hardware efforts.

The contributors were polled to determine the types and quantities of tests that they plan to accomplish in the 2003-2004 time period. The following matrix is a summary of those plans:

Table 1.1: Task 1 Test Matrix

	Georgia Tech	GRC/GEPS	Notes
Tensile	-	24	Includes Exposed, Baseline
LCF	88	106	Includes Hold Time, Exposed, Baseline, Vacuum, Grain Effects
TMF	30	-	
Torsion LCF	25	-	
Creep	48	50	Includes Exposed, Baseline
FCGR	68	54	Includes Static, Hold Time
Exposure	-	12	
Fracture Toughness	45	-	
Coated LCF	25	-	
Additional (TBD)	-	45	Sub-Task 1.4, exposed, interaction, path dependent

Based on this input, 80 DS GTD-111 slabs have been ordered for specimen machining. In the interest of consistent structure, one size of slab was ordered (9" by 5" by 0.6"). Currently, the plan includes Nimonic-263 as the Combustor material. That selection is being confirmed before ordering material. It is not expected to delay the program as the lead time for material purchase is expected to be short for Nimonic-263 or other wrought material (compared to cast slabs).

Sub-Task 1.2 - Analytical Life Assessment Model Development

GEPS and Georgia Tech are the main contributors for this task. One accomplishment is the modeling of compact tension test specimen to enable analysis of fracture toughness test data that will be generated.

Additionally, orthotropic stress intensity factors for surface cracks oriented in longitudinal and transverse orientations (DS GTD-111) have been calculated and compared using two software packages, ANSYS/GE_FRANC3D and GRC 3DFAS. The solutions are in agreement. Also, cooling holes at the trailing edge of the 7FA Stage 1 bucket have been modeled. The model will be used to compare fracture mechanics life prediction to the performance of field hardware.

Sub-Task 1.3 - Experimental Verification of Life Assessment Methodology

This subtask has not been initiated. Activities are slated to begin in mid-2005.

Sub-Task 1.4 - Field Validation of Life Assessment Methodology

Groundwork is being laid for the experimental verification of the models developed in Sub-Tasks 1.1 and 1.2.

In order to ensure that the program fully addresses the needs for IGCC applications, the Syngas fuel composition, and gathering field information regarding the effect of Syngas on HGP hardware is being investigated. Information on HGP hardware from TECO Polk #1 has been gathered from the Houston services shop. A follow up request for more detailed information and for schedules of planned outages for other IGCC equipment has been made to enable a more detailed hardware evaluation.

GE is also working to get customer input as to the issues they may be experiencing, and in this manner the GE representative at TECO has been contacted to arrange a meeting (4^{th} qtr 2003 or 1^{st} qtr 2004) with that customer.

Task 2 Status/Discussion:

Overview: Under this task new technologies to determine the health of advanced technology coal IGCC and natural gas power plants is planned to be evaluated and demonstrated. Technologies developed for the aerospace industry leveraged via collaborations with GEAE and SNL. The work is divided into the following subtasks:

Subtask 2.1 – Define Coal IGCC Power plant Requirements: The monitoring requirements will be established for coal IGCC and natural gas power plants. Needs will be identified and prioritized using Quality Function Deployment (QFD) and other "Six Sigma" quality tools that are now used widely throughout GE. The Critical-To-Quality (CTQ) characteristics of the required sensors, systems, and controls will be identified during this process.

Subtask 2.2 - Sensor Capability Studies: Laboratory trials will be performed to baseline the accuracy and repeatability of new sensors. Technologies will be considered from all available sources, specifically including a new fuel quality sensor being developed with SNL under the DOE Smart Power Turbine program. The capability of the fuel quality sensor will be tailored specifically for coal IGCC fuel constituents.

Subtask 2.3 - IR Pyrometer for Condition Based Maintenance: Infra-Red (IR) pyrometer temperature measurements will be validated using experimental data from the laboratory and field data from at least two turbine installations. The pyrometer data will be compared to predictions of metal temperature from aerodynamic and heat transfer models.

Subtask 2.4 - Sensor Networking and System Integration: New strategies for networking and system integration of sensor, data processing, compression, and transmission elements from various distributed sources around the power plant will be developed.

Subtask 2.5 - Field Deployment and System Validation: Field trials and long-term validation of new sensors and data systems will be performed. Sensor technologies developed in the DOE Smart Power Turbine program, as well as new combustion sensors and robotic inspection technologies being developed by GE, will be field-tested at coal IGCC and natural gas powerplants.

Task 2 Discussion:

Subtask 2.1 – Define Coal IGCC Power Plant Requirements:

The GE team conducted a Six Sigma based Quality Function Deployment (QFD) to identify and rank the sensor requirements of a coal/IGCC power plant. IGCC Plant Monitoring Critical to Quality (CTQ) goals (Figure 2.9) were developed from customer requirements to IGCC gas turbine sub-system CTQs (Figure 2.10) to gas turbine sensor requirements (Figure 2.11). Sensors needed for development were prioritized.

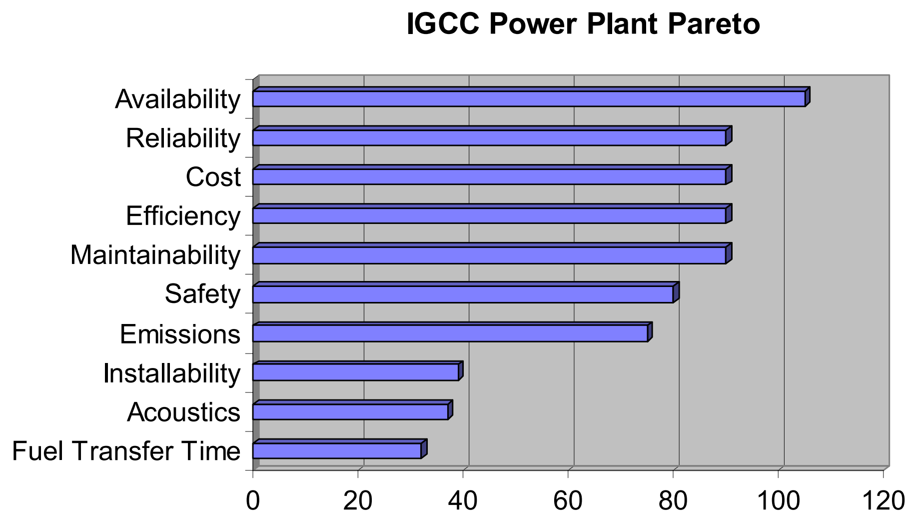


Figure 2.9: IGCC Plant Critical to Quality

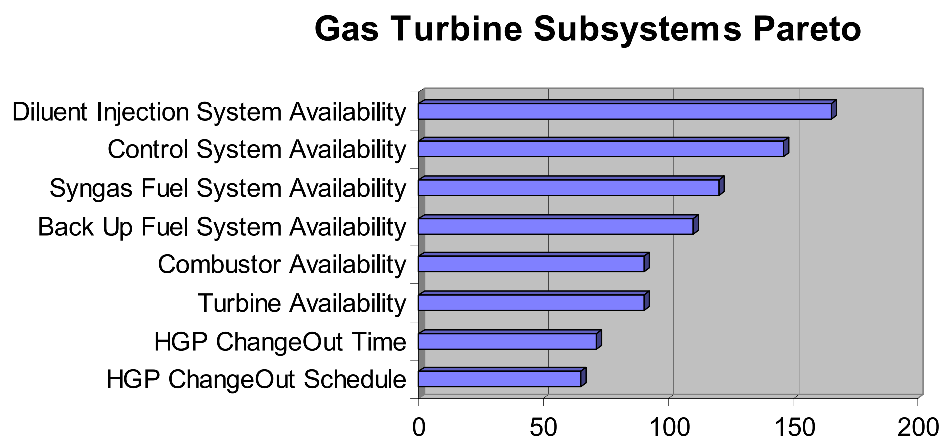


Figure 2.10: Gas turbine sub-systems CTQs

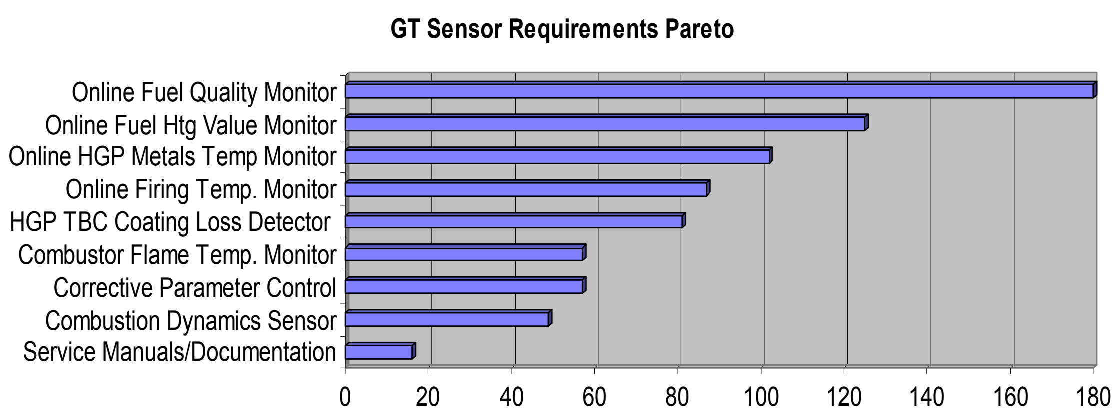


Figure 2.11: Gas turbine sensor requirements

Functional specifications were generated for the identified sensors. In order to begin the development of the fuel quality sensor, the fuel species variation for the IGCC fuel at TECO has been characterized.

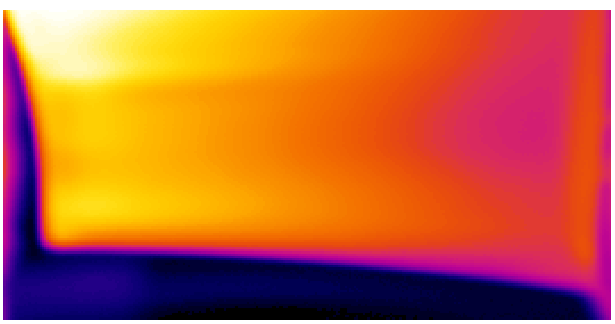
Subtask 2.2 - Sensor Capability Studies

Coal/IGCC gas turbine monitoring sensors are needed, in order of priority, for measurement of fuel quality, fuel heating value, hot gas path metal temperature, firing temperature, TBC coating loss, combustion flame temperature, exhaust emissions (needed for corrected parameter control), and combustion dynamics. Some of these requirements can be met simultaneously with one sensor; for example, hot gas path metal temperature, firing temperature, and TBC coating loss can all be determined using the pyrometer.

At present; the fuel quality sensor, the fuel heating value sensor, and the flame temperature sensor are being developed under the DOE Smart Turbine Program. The exhaust emissions sensor is being developed under a separate GE funded program. These sensors will be taken to the next level in application to a coal/IGCC gas turbine under this program. The laser induced breakdown spectrometry (LIBS) technique is also being evaluated for measuring fuelborne and airborne inlet particulates.

Subtask 2.3 - IR Pyrometer for Condition Based Maintenance

Pre-determining the Thermal Variation of the Buckets
Infrared (IR) images of a stage one bucket are shown in Figures 2.12 and 2.13.



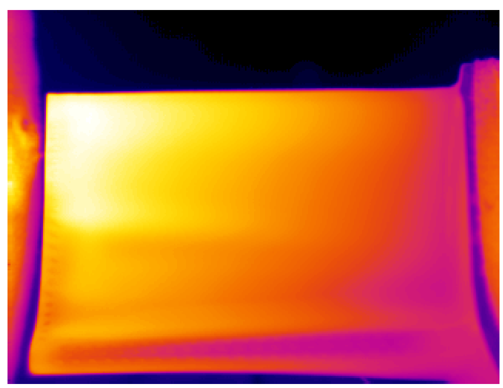


Figure 2.12: Leading edge of pressure side of bucket
Figure 2.13: Trailing edge of pressure side of bucket

Determining Absolute Temperature and Emissivity using Spectroscopy
Spectroscopy measurements were performed on GT-1 during the initial startup on March 25, 2003. The data for twelve different power levels is shown in Figure 2.14.

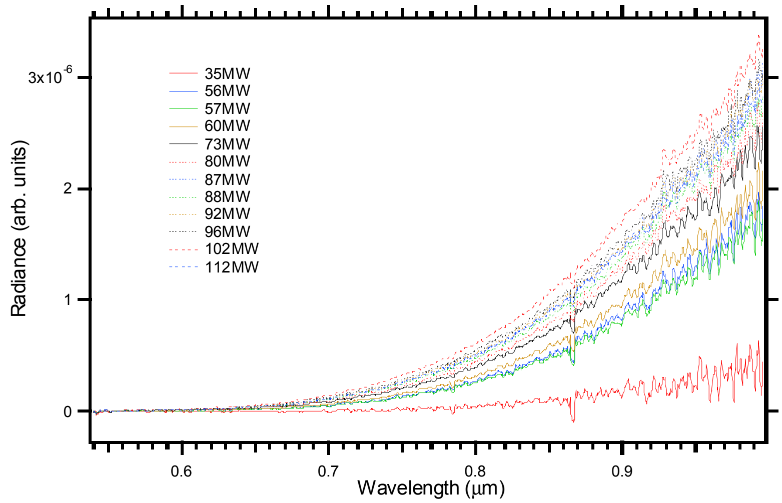


Figure 2.14: Spectra from GT-1 wheel, corrected for spectrometer efficiency

The emissivity values calculated for each power level are show in Figure 2.15. These values represent an average emissivity over the entire wheel. If the lowest power level is ignored (where there are large errors) there is a close agreement between the values at each power level, indicating an average emissivity of 0.54.

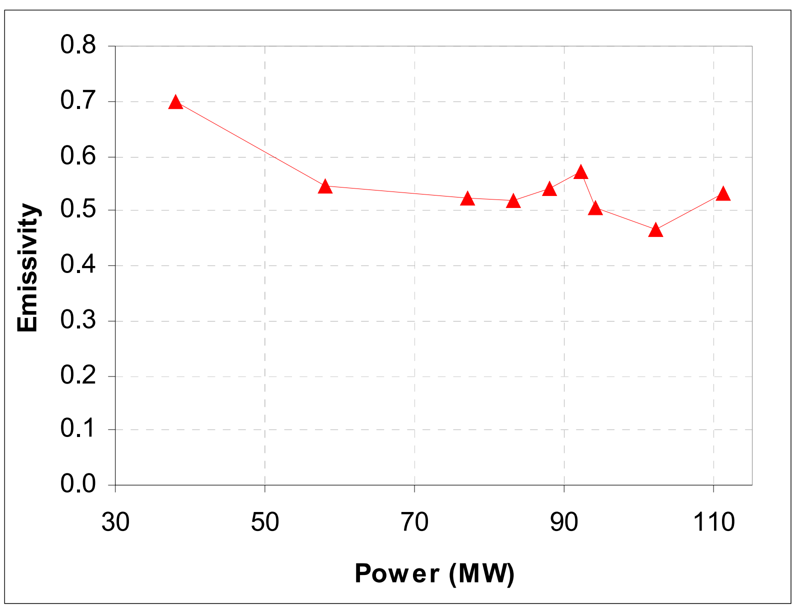


Figure 2.15: Average wheel emissivity of the buckets back-calculated from the temperature difference between the Land pyrometer and the spectrometer measurements

Task 3 - Status/Discussion:

Overview: This report details progress for Task 3 – Advanced Methods for Combustion Monitoring and Control. The contributors to Task 3 are the GE Global Research Center, GE Power Systems (GEPS) Energy and Environmental Research, GEPS Reliability Engineering, and Sandia National Laboratory (SNL). Task 3 consists of 3 sub-tasks as follows:

> Sub-Task 3.1 - Physics-based Combustion Process Modeling: will develop physics-based models of combustor and fuel system dynamics critical for improving the understanding of performance characteristics for coal IGCC and DLN combustors. The sub-task will combine theoretical modeling with system identification experiments to develop physics-based models for predicting combustion performance and operability. The models will be validated using combustor and other operational data from full-scale combustion systems, including data from power plants, and lay the foundation for development of active control techniques.
>
> Sub-Task 3.2 – Development of Active Control Methods: Control strategies for improving combustor operability and performance while reducing or maintaining emissions levels will be developed and tested. System models developed in the previous sub-tasks will be used to develop and test open- and closed-loop active controllers in computer simulations. Robust control components, including feedback sensors and control actuators, will be identified and tested.
>
> Sub-Task 3.3 – Combustor Health Monitoring and Prognostics: The systems and concepts described in the previous sub-tasks will be evaluated using a variety of test facilities. Successively larger-scale testing will be performed, including annular or full combustor can tests, as appropriate for the power plant application.

Only sub-task 3.1 has been initiated in this reporting period. This sub-task will address the combination of theoretical modeling with system identification experiments to develop physics-based models for predicting combustion dynamics characteristics in DLN systems. The development of physics-based models of combustor and fuel system dynamics is critical for improving the understanding of combustion-driven pressure oscillations and for guiding design of suppression and control methods. The models will be validated using dynamics data from full-scale DLN combustion systems, including actual engine data. The resulting models will lay the foundation for the development of combustion dynamics suppression and control techniques, as well as to provide a basis for predicting dynamics characteristics of new combustor design concepts.

Task 3 Discussion:

Combustion Dynamics Modeling

Combustion dynamics (or instability) arises from acoustic-combustion interaction. When acoustic perturbations gain energy from flame heat release, perturbations tend to grow in amplitudes, resulting in large amplitude acoustic oscillations. The oscillations are usually at discrete frequencies that are very close to combustor acoustic system natural frequencies.

Combustion driven oscillations often pose significant problems in the operation of gas turbines. To develop effective methods to eliminate these combustion instabilities in a system, one requires a good model of system dynamics that includes the interactions between different combustor components. The purpose of the model is two fold. First, it should validate our understanding of combustion dynamics including the dynamic effects of fuel modulation. Second, it should provide a simple but solid foundation for nonlinear dynamical analysis and control design tools to be applied.

A physics-based combustor dynamics-modeling tool was developed in GE Global Research Center (GE GRC). In this model, the physical processes including fundamental acoustic characteristics of the combustor systems, fuel supply system, acoustic-flame interaction, and flame heat release are captured. The acoustics of the combustor system is modeled using the following standard acoustic equations that account for the effect of heat release, mean flow, and temperature variations upon wave propagation:

Mass: $$\frac{\partial \rho'}{\partial t} + \nabla \cdot (\bar{\rho}\vec{u}' + \rho'\vec{u}) = 0 \qquad (1)$$

Momentum: $$\bar{\rho}\left(\frac{\partial \vec{u}'}{\partial t} + \vec{u}' \cdot \nabla \vec{u} + \vec{u} \cdot \nabla \vec{u}'\right) + \rho'\vec{u} \cdot \nabla \vec{u} = -\nabla p' \qquad (2)$$

Energy: $$\frac{\partial p'}{\partial t} + \nabla \cdot (p'\vec{u} + \bar{p}\vec{u}') = \frac{\gamma - 1}{\gamma} q' \qquad (3)$$

where a prime denotes a fluctuating quantity and an overbar a mean quantity. These equations can be simplified in various regions of the combustion and fuel supply system. In ducts and piping with diameters much smaller than the wavelength of oscillations and with constant or slowly varying temperatures, the acoustic field is a one-dimensional longitudinal acoustic wave field. In each of these approximately one-dimensional regions, the exact solution for the acoustic field can be written as:

$$p_j' = (A_j e^{-ik_j x/(1+M)} + B_j e^{ik_j x/(1-M)}) e^{i\omega t} \qquad (4)$$

$$u_j' = \frac{1}{\overline{\overline{\rho_j c_j}}} (A_j e^{-ik_j x/(1+M)} - B_j e^{ik_j x/(1-M)}) e^{i\omega t} \qquad (5)$$

where A and B are the magnitudes of acoustic waves propagating in the positive and negative x directions at speeds of c+U and c-U, respectively, ω is the angular frequency, $k=\omega/c$ is the acoustic wavenumber, and the subscript, j, denotes a region of the system.

Using boundary conditions at the combustion flow inlet and outlet, and matching conditions for equation (4) and (5) at the interfaces of different combustion sub-systems, one obtains a model of coupled algebraic and differential equations. The model can be used to calculate system natural resonant frequencies, growth rates, and modal shapes. Some of these acoustic modes will gain energy from flame heat release and grow in amplitudes. These modes are called unstable modes (growth rate > 0). The other modes interact with flame in such a way that their amplitudes will decay from initial perturbations. These are called stable modes (growth rate < 0). The unstable modes are associated with combustion dynamics. The structure of the model has been supported by initial experimental results described below and also has been compared with other published works in this field.

Model Validation

The model described above was applied to the single nozzle rig (SNR) described in the previous section. Dynamics data were obtained from the rig using 6 dynamic pressure transducers. The locations of the transducers were shown in Figure 3.3.

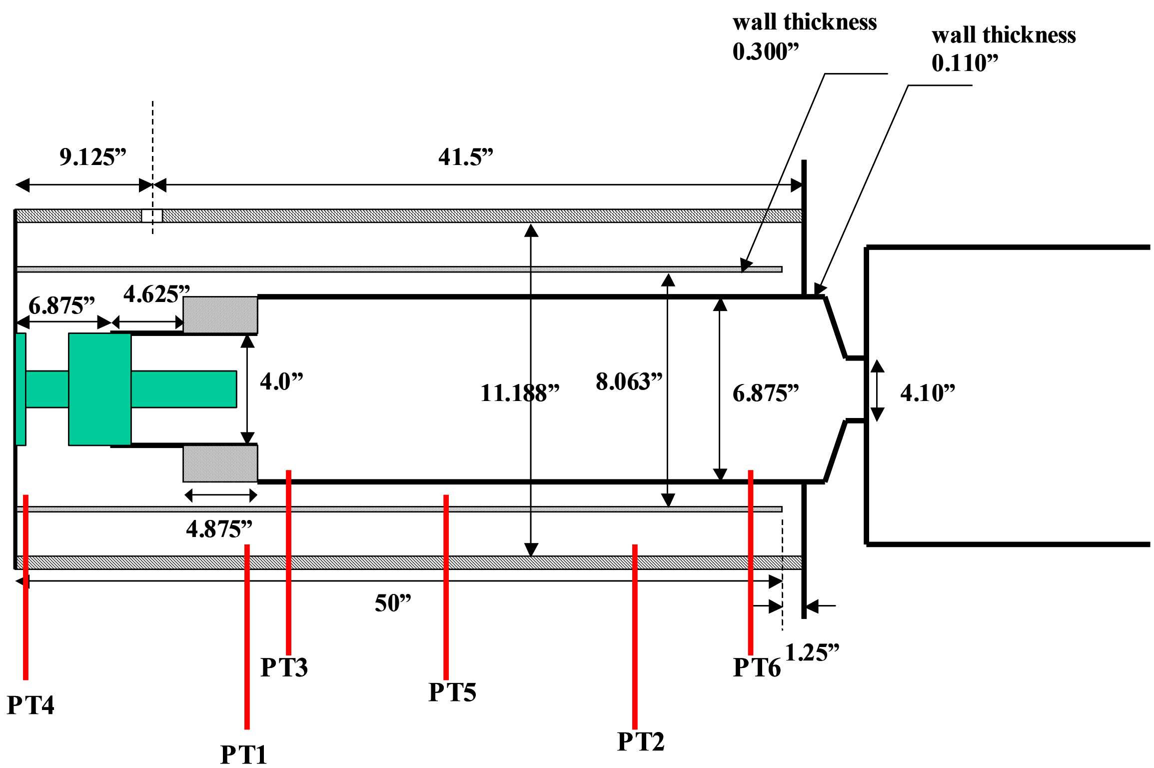


Figure 3.3: Dynamic pressure transducer locations

At the baseline operation condition, the combustor rig has a distinctive tone of around 180Hz, with amplitudes at certain locations above 0.8 psi, as shown in Figure 3.4.

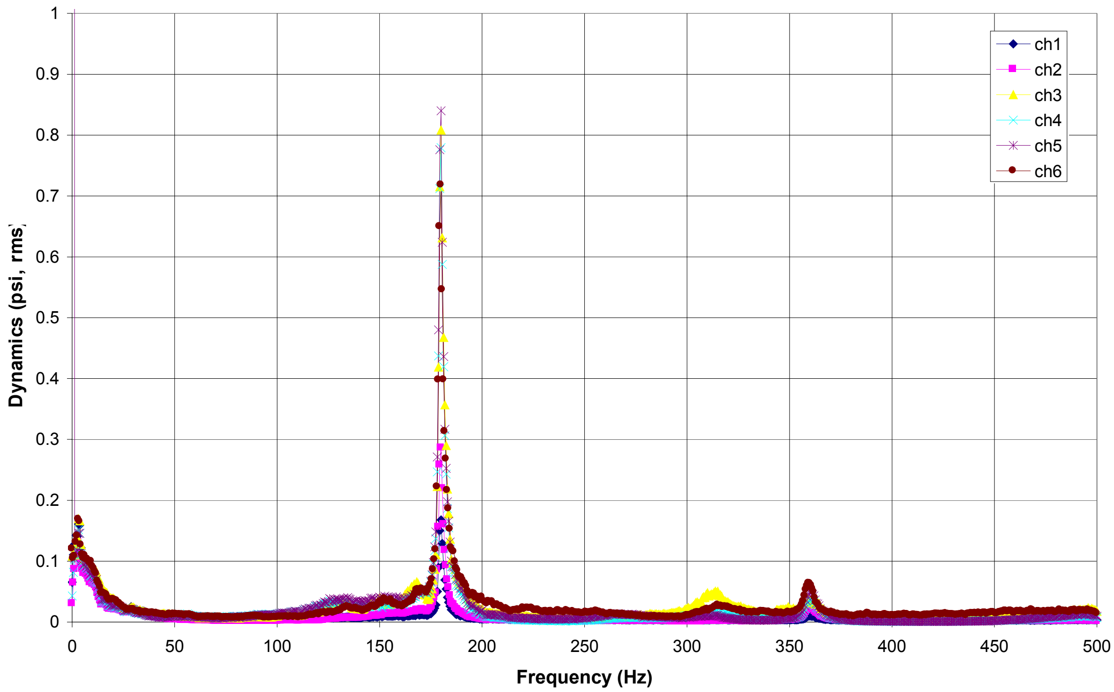


Figure 3.4: Measured dynamics data in SNR at the baseline operation condition

The frequencies and growth rates of all the dynamic modes below 300Hz predicted by the model at the same rig operation condition are shown in Figure 3.5.

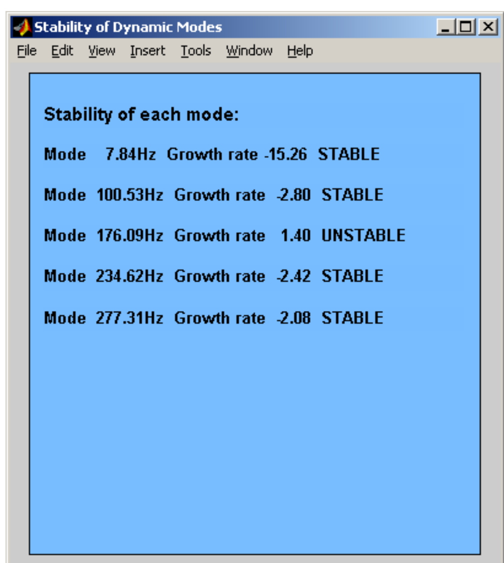


Figure 3.5: Dynamic modes predicted by the model

There are totally 5 modes for the combustor system below 300 Hz. The mode at 176Hz is an unstable mode, all others are stable modes. The model successfully predicted the dynamics observed in tests.

The modal shape at 176Hz predicted by the model is also compared with the measured dynamics at the six pressure transducer locations. The results are shown in Figure 3.6. It can be seen that both the magnitude and phase of the 176Hz mode calculated by the model agree very well the test data.

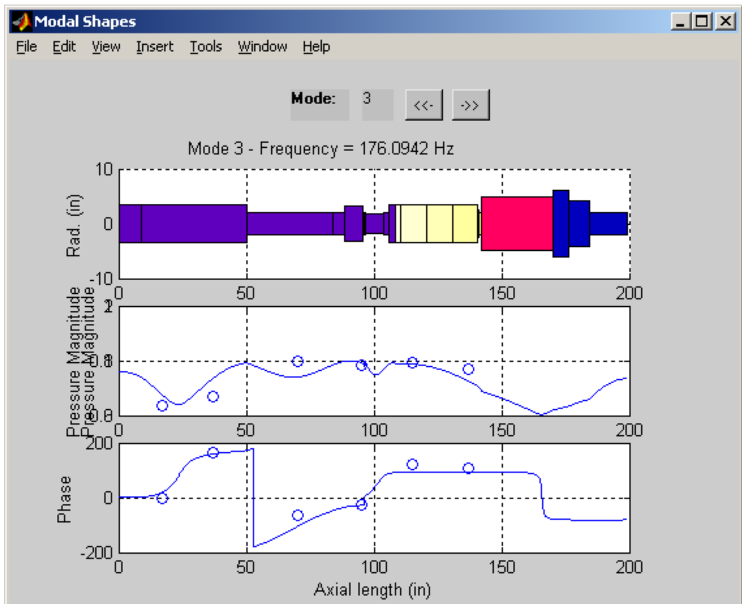


Figure 3.6: Calculated dynamics modal shape compared with experimental data

Validations using the SNR data show that the model is accurate in calculating the dynamics frequencies, stability, and modal shapes. The model will be used to design dynamics active control schemes.

System Dynamics Time Domain Equations

The model must first be converted into differential equations that can capture dynamic processes in a combustion system in time domain in order to be used for active control design. The details of this transformation are given below.

Using the mass, momentum, and the energy equations (1,2,3) and partially differentiating equation (2) with x and differentiate equation (3) with t, and combining the resulting two equations yield

$$\frac{1}{c^2}\frac{\partial^2 p'}{\partial t^2} - \frac{\partial^2 p'}{\partial x^2} = \frac{\gamma - 1}{c^2}\frac{\partial q'}{\partial t} - \frac{\gamma R}{c^2}\bar{\rho}\frac{\partial}{\partial t}(u'\frac{\partial \overline{T}}{\partial x}) \qquad (6)$$

Using the modal analysis method the acoustic pressure p' can be written in Fourier series as

$$p'(x,t) = \bar{p}\sum_n \eta_n(t)\psi_n(x) \tag{7}$$

where $\eta_n(t)$ is the magnitude of the n^{th} dynamics mode of the combustor, and $\psi_n(x)$ is the weighting function or modal shape. Substituting equation (7) into equation (6) gives

$$\ddot{\eta}_n(t) + 2\zeta_n\omega_n\dot{\eta}_n(t) + \omega_n^2\eta_n(t) = \frac{\gamma-1}{\bar{p}}\frac{1}{\int_0^L \psi_n^2 dx}\int_0^L \psi_n(x)\frac{\partial q'}{\partial t}dx \tag{8}$$

where ζ_n is the system damping coefficient of the n^{th} mode and L is the whole combustor length. The term on the right hand side of equation (8) is the source term of the flame heat release.

Using the new heat release model developed jointly by GRC and Georgia Institute of Technology, we have

$$\frac{Q'}{\bar{Q}}(t) = f_n\frac{u'_f}{\bar{u}_f}(t-\tau_f) + g_n\frac{\phi'_f}{\bar{\phi}_f}(t-\tau_g) \tag{9}$$

The first term on the right hand side of the equation represents heat release fluctuation caused by flow velocity fluctuation at the flame base, u'_f, the second term is heat release fluctuation caused by fuel-air ratio fluctuation at the flame base, ϕ'_f. Due to distributed flame shape, heat release will react to velocity fluctuation and fuel-air ratio fluctuation at flame base with time delays of τ_f and τ_g, respectively. Fuel-air ratio at the flame base is related to fuel air ratio at the fuel injection location by the flow convection speed:

$$\frac{\phi'_f}{\bar{\phi}_f}(t) = \frac{\phi'_{inj}}{\bar{\phi}_{inj}}(t-\tau_c) \tag{10}$$

Fuel air ratio fluctuation can be written as fuel fluctuation and air fluctuation at the fuel injection location using

$$\frac{\phi'_{inj}}{\bar{\phi}_{inj}} = \frac{\dfrac{m'_{fuel}}{\bar{m}_{fuel}} - \dfrac{m'_{air}}{\bar{m}_{air}}}{1 + \dfrac{m'_{air}}{\bar{m}_{air}}} \tag{11}$$

where m'_{fuel} is mass flow fluctuations of fuel from nozzle fuel injection holes and m'_{air} is air flow fluctuations on the air side of the nozzle at the fuel injection location.

Fuel fluctuation comes from modulation by air pressure fluctuation and by dynamics source located upstream the fuel line (in this case, the active control valve)

$$\frac{m'_{fuel}}{\bar{m}_{fuel}}(t) = a_n\frac{m'_{valve}}{\bar{m}_{fuel}}(t-\tau_a) + b_n\frac{p'_{air}}{2\Delta P}(t-\tau_b) \tag{12}$$

where m'_{valve} is mass flow fluctuations generated by the valve and ΔP is the fuel side pressure drop across fuel injection holes. p'_{air} is air pressure fluctuations on the air side of the nozzle at the fuel injection location. τ_a is the time delay from valve to fuel injection fluctuation and τ_b is the time delay from pressure fluctuation to fuel injection fluctuation. The values of a_n and b_n change with acoustic modes.

Combining equations (9-12) yields

$$\frac{Q'}{\overline{Q}}(t) = f_n \frac{u'_f}{\overline{u}_f}(t-\tau_f) + g_n \frac{a_n \frac{m'_{valve}}{\overline{m}_{fuel}}(t-\tau_a-\tau_c-\tau_g) + b_n \frac{p'_{inj}}{2\overline{\Delta P}}(t-\tau_b-\tau_c-\tau_g) - \frac{u'_{inj}}{\overline{u}_{inj}}(t-\tau_c-\tau_g)}{1+\frac{u'_{inj}}{\overline{u}_{inj}}(t-\tau_c-\tau_g)} \tag{13}$$

Equation (8) describes the dynamics amplitude growing process in time domain as a result of flame heat release. The flame heat release process in time domain is described in detail in equation (13). They can be used combined to develop an active control strategy to reduce combustion dynamics.

<u>Control Design Considerations</u>

A combustion dynamics control strategy based on unsteady fuel addition is being developed. The technique has been demonstrated extensively on small-scale combustion systems and results of these studies may be found in the literature (see, for example Ref. 2). In the present work, this strategy is being adapted for use in full-scale power generation gas turbines. To this end, detailed controller design is being performed through the use of the system model described above. In addition, experiments are being performed to understand the limits of control authority, or actuator effectiveness when using high-frequency fuel modulation to effect control in current DLN combustion hardware. Preliminary results from these activities are described below.

The combustion dynamics model described above has been used extensively to predict unstable modes in various combustor designs. In addition, it is being used to develop model-based control schemes for suppressing combustion dynamics. To be effective for the latter, it is recognized that the model must adequately represent certain key behavior in the combustion system including:

- linear behavior during weak thermo-acoustic instability
- nonlinear behavior during strong thermo-acoustic instability
- the effects of fuel forcing on overall system dynamics

In order to apply nonlinear dynamical analysis tools (such as bifurcation theory and manifold descriptions), the model was transformed to an analytical form in the time-domain (see Eqs. 8-13 above). The resulting equation is a closed-loop delay-differential-equation (DDE) with a forced input, the block diagram for which is shown in Figure 3.7. This basic model structure will be used as a starting point for detailed control design to be performed during the next quarter of the program.

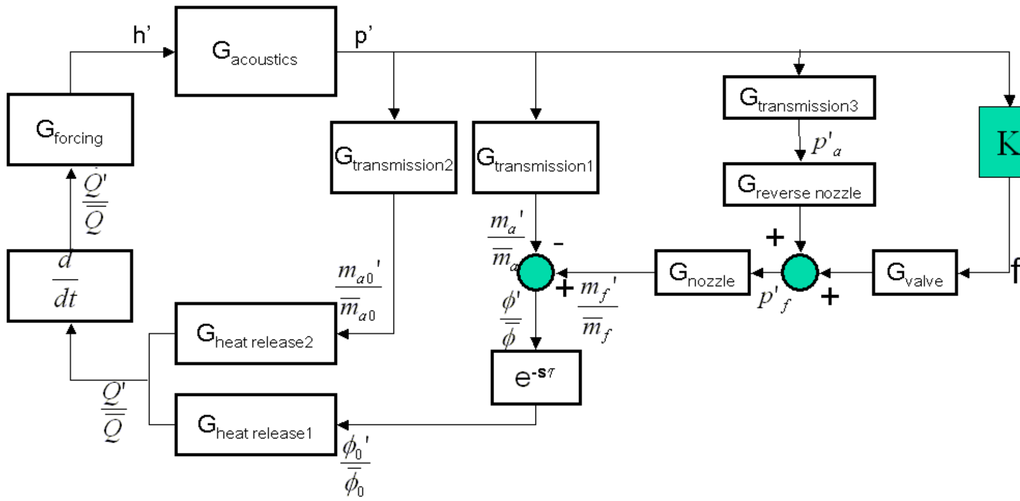


Figure 3.7: Block diagram of Delay Differential Equation thermo-acoustic model. The block K represents the controller.

<u>Preliminary Investigation of Fuel Forcing</u>

Several experiments were performed to gain understanding of the effects of unsteady fuel modulation on the behavior of the combustor. A high-bandwidth fuel control valve was coupled to the fuel premixer on the single-nozzle rig. The effects of fixed-frequency fuel modulation on the combustor operability and dynamics was examined. Control strategies using fuel modulation generally require the ability to modulate fuel flow at frequencies in the range of those where combustion dynamics occur. Because the identified thermo-acoustic oscillation frequencies were significantly higher than those which off-the-shelf fuel valves could achieve, high frequency modulation valve technologies were explored and an experimental valve from Georgia Institute of Technology was selected for trials. The GaTech fuel valve was coupled to the DLN premixer and open loop fuel forcing experiments were performed over a range of frequencies from 50 to 200Hz.

Initial experiments focused on general combustor operability characteristics. An important measure of operability is the combustor lean blowout (LBO) limit. Results from a series of LBO experiments both with and without fuel modulation are shown in Figure 3.8.

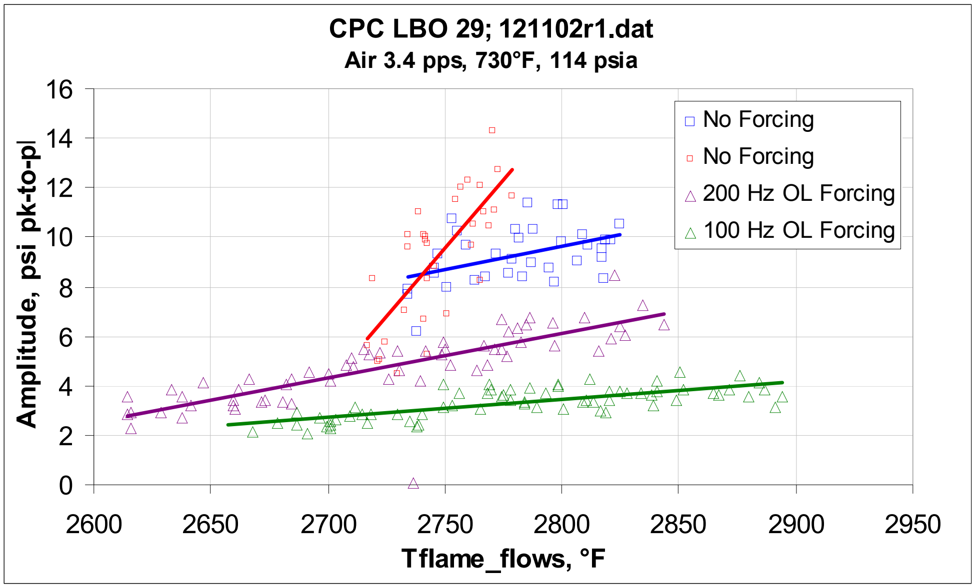


Figure 3.8: Lean blowout limits measured with and without fuel modulation

We see an extension (improvement) in LBO when fuel modulation is incorporated. This suggests that there is an intrinsic change in combustion stability when the fuel flow is modulated at high-frequency. The reason for this is unclear at present and further experiments are planned to elucidate the physical mechanism responsible for this performance improvement.

The second set of experiments aimed to characterize the fuel valve dynamic properties (frequency response if a linear system). Initial results indicate the valve to have an effective bandwidth of 300Hz – well above the oscillating frequency of the thermo-acoustic instability. As part of the second set of experiments, the effect of open-loop forcing using fuel modulation was investigated. Qualitatively there is an attenuation effect observed at various forcing frequencies and amplitudes, as in shown in Figure 3.9.

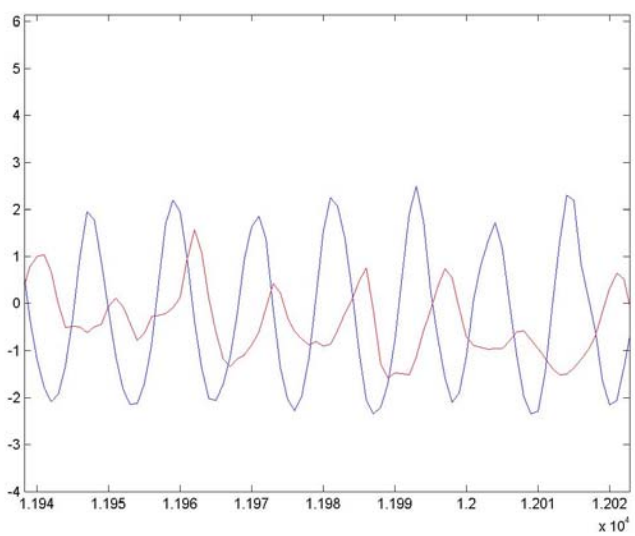


Figure 3.9: Thermo-acoustic oscillation with (red) and without (blue) fuel modulation

However, new dynamics appear and grow as the forcing is increased. This is illustrated in the Power Spectral Density comparison in Figure 3.10.

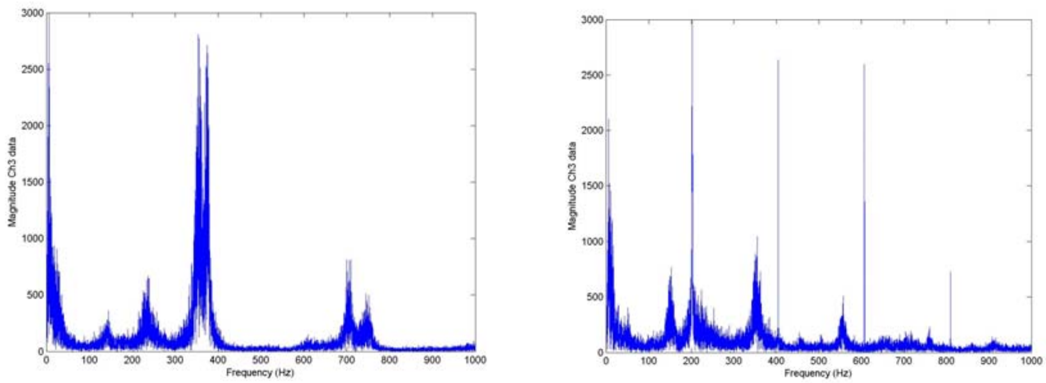


Figure 3.10: Power spectral density plots of pressure inside the combustion chamber with no fuel modulation (left) and 200Hz modulation (right)

The results from these experiments were used to modify the model structure to incorporate the fuel forcing mechanism.

The third set of experiments, currently being undertaken, are cold flow experiments to further the characterize the valve and amplifier which drives the modulating signal. The intent is to establish a valve operating profile that satisfies thermal constraints, current/voltage constraints, as in Figure 3.11, inlet static flow variability and downstream back propagation effects from the nozzle. The amplifier is being tested for nonlinear effects and harmonic distortion.

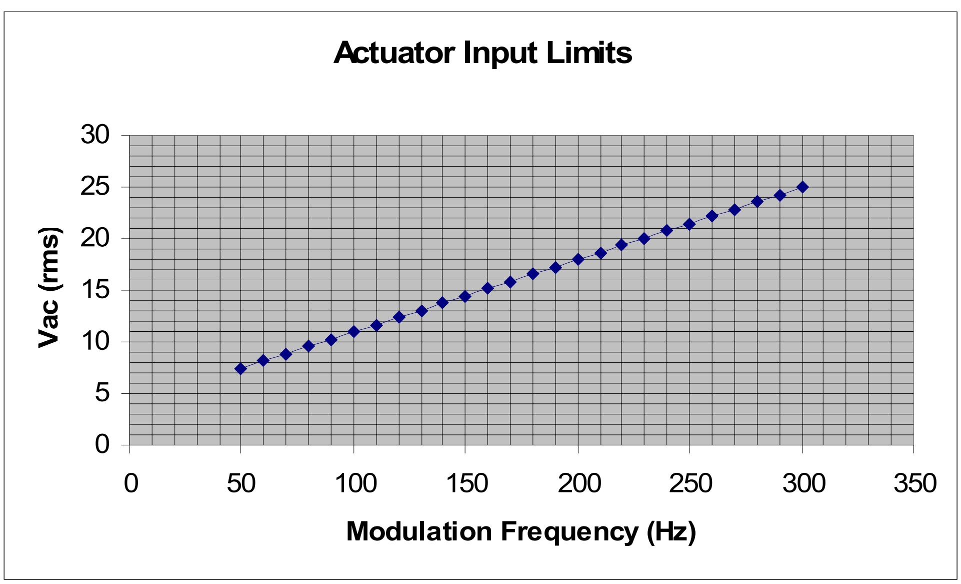


Figure 3.11: Voltage applied to the valve constraints

The fourth set of experiments will use the bifurcation diagram of the model and hot flow conditions to explore the dynamic system behavior including the actuator effects. The aim is to have a predictive capability, using the model, of how the system will react to a given fuel forcing condition. This thorough experiment will test various fuel forcing amplitudes and frequencies over a range of equivalence ratios, encompassing both lean and rich induced thermo-acoustic instabilities.

The data from Experiment set four will be used to calibrate the model, and validate our assumptions regarding the fuel forcing mechanism. If rather our assumptions are disproved, then the model will be parsimoniously modified in attempt to capture the observed behavior. This iterative cycle of inductive experimentation followed by inductive model modification will continue until we are satisfied with the predictive capabilities of the model. Only once this is achieved can control design proceed.

As previously discussed, the quality of the model will directly impact the effectiveness of the controller. Other influencing factors include the control authority imposed by the valve and sensing limitations. For these reasons a large part of the schedule is devoted to the system and sensor modeling and actuator characterization. While these tasks are being completed, various control design strategies are being evaluated for their applicability and implementation issues.

Non-model based control designs are also being evaluated, though they are expected to give larger level of conservatism, and hence lower performance. They are also unable to explain secondary peaking phenomena that tend to appear in the controlled system. Nevertheless they have been demonstrated to work in the literature and so shall be benchmarked also.

The controller design tasks are scheduled to be completed in November with the first round of hot flow combustion control testing before the end of this year.

Task 4 - Status/Discussion:

Overview: This report details progress for Task 4 – Information Technology (IT) Integration. The contributors to Task 4 are GE Power Systems (GEPS) Energy Services Technology, which includes the Smart Services and Operations Center organizations, and GEPS Optimization Software. Task 4 consists of 3 sub-tasks as follows:

> Sub-Task 4.1: This sub-task is to extend the functionality of GE's GateCycle™ commercial heat-balance simulation software in order to model complete integrated gasification combined-cycle ("IGCC") power plants, and to use this extended GateCycle™ software to build and configure the online EfficiencyMap™ performance monitoring software system at a selected IGCC site to provide coal IGCC powerplant performance data in real time.
>
> Sub-Task 4.2: This sub-task will identify and integrate information technologies for powerplant condition assessment and condition based maintenance.
>
> Sub-Task 4.3: This sub-task will evaluate the information technologies for powerplant condition assessment and condition based maintenance identified in sub-task 4.2 at a minimum of two GE "F" Technology gas turburbine powerplants (at least one of these will be a coal IGCC powerplant).

Task 4 Discussion:

Sub-Task 4.1: Performance Modeling for Coal/IGCC Powerplants

The primary focus of this sub-task is to extend the functionality of GE's GateCycle™ commercial heat-balance simulation software in order to model complete integrated gasification combined-cycle ("IGCC") power plants, and to use this extended GateCycle™ software to build and configure the online EfficiencyMap™ performance monitoring software system at a selected IGCC site. In support of this work, it is necessary to enhance the database foundation, property calculations, convergence routines and unit operation equipment models of the GateCycle™ software.

During the development of the SQL database version of GateCycle, a key issue that had to be resolved was the speed of database access. Preliminary designs and test implementations proved to be unacceptably slow, and the basic architecture and some of the underlying core database routines had to be extensively reworked to improve the speed. Various design alternatives were explored, including ADO bulk writes, but these proved to be even slower than the initial test implementations. The key design change that brought the database access speed up to an acceptable level was to rework the SQL stored procedure calls to combine thousands of separate database calls into only a few.

Other problems encountered during the development of the SQL database version were the initialization of data structures and issues relating to program startup. With the new SQL database design, considerably more of the configuration and program data is now stored in the database, rather than compiled directly in code structures. In addition, additional data structures have now been added that have considerably increased the complexity of the data structures needed, including more complex streams, table structures, the concept of libraries, as well as configuration constants and default data. As a result, additional code had to be designed, written and tested to properly initialize the database system, and also to deal with the considerable amount of data that needs to flow at program startup. It is anticipated that additional development and tuning of the code and database will be required to improve the speed of startup before the final commercial release.

While reworking the basic architecture of GateCycle to integrate it with the SQL database code, every effort was also made to improve the basic code and database structures to reduce the effort that would be needed to continue to support and extend the program in the future, particularly considering the substantial extensions that will be implemented to support IGCC modeling. The basic structures were modified to move constants that had been compiled in the code itself instead into the SQL database (such as default data values, user-selected engineering methods for equipment models, etc.). This will make the development of the IGCC extensions less error prone and should make the code easier to maintain and extend in the future.

Sub-Task 4.2 - Coal/IGCC Powerplant Data Integration

The Universal On-Site Monitor (UOSM) is being developed to collect and integrate data from multiple condition monitoring applications at a power plant: turbine-generator controls, plant distributed controls, emissions monitoring, etc. Pilot testing of UOSM hardware and software is in-progress in several GE development laboratories and pilot powerplants. Progress to-date is discussed below.

System Development and Validation

The UOSM hardware and GE-ICAS2002 condition monitoring system have been installed at the initial MS7001FA+e test site. This system utilizes approximately 50 separate software applications and rules. Synergy software was developed by GE-FANUC to monitor and integrate program anomaly outputs. Several sensor anomalies have been detected and corrected, resulting in improved gas turbine performance and life of the turbine components.

Gas turbine rules cover operation profiles, diagnostic algorithms, anomaly detection and analysis, performance modeling, parts lifing, and remote services. A model-based diagnostics package is being developed to facilitate comparing the individual units to the fleet baselines.

Steam turbine rub detection algorithms have been developed and deployed. Rubs are classified by severity, effect on operations – delay in startup, as a possible trip cause, incorrect controller setup (i.e., constant values), system integration incorrect, or an operator improper operation.

Generator rules have been deployed and are being expanded. This rule package is a combination of crisp and fuzzy rules that determine generator performance and monitor for stator and rotor anomalies (i.e. shorted field, grounds, hydrogen purity).

Upcoming UOSM deployments include:

- Frequency Oscillation detection – this program detects changes in frequency and amplitude of key parameters. These oscillations are believed to be predictive of turbine anomalies.
- MKVI Diagnostics – this program allows remote assistance with control system anomalies.
- Corrected Parameter Control deployed to the OSM for development.
- Sectional Efficiency Calculations for Combined Cycle plants.

Duke Fayette Site Installation

The hardware installation was delayed, but is expected to be completed by the end of the year. This does not affect the UOSM validation activities described above.

TECO Polk #1 Site Installation

The hardware has been installed, the DCS site survey was reviewed, and the gasification plant tag list was reviewed. An initial design for acquiring the required plant data was completed. The next step includes the identification of require parameters for the EMAP performance model and the integration of all required parameters into the UOSM.

Sub-Task 4.3 - Information Technology (IT) Validation

Integration of program activities with IT applications being developed outside the program is on-going. Key IT applications are the Condition Assessment Platform, Residual Life Estimator, and Power Smarts™ customer web portal.

Conclusions

Task 1- Hot Gas Path Parts Life Prediction:
Substantial progress has been made in three of the four subtasks initiated during the first six months of the program. No conclusions have been made for Task 1, Combustor and Hot Gas Path Parts Life Prediction at this time. Materials testing and modeling are continuing.

Task 2 - Powerplant In-Service Health Monitoring:
Substantial progress has been made in the first three subtasks during the first six months of the program. The team has conducted a Six Sigma based QFD to identify and rank the sensor requirements of a coal/IGCC power plant. Sensors needed for development were prioritized. Sensor Functional Specifications for the identified sensors have been generated.

Under the IR Pyrometer task (sub-task 2.3), the GE team has worked on pre-determining the thermal variation of two sets of stage 1 turbine buckets before they were installed in the MS7001FA+e gas turbines at the Duke Maine Independence powerplant. The team installed, calibrated, and determined the Line-of-Sight (LOS) of the pyrometers in these gas turbines and obtained temperature data during operations. Absolute temperature and emissivity was measured using spectroscopy in one of these gas turbines. The methodology of predicting temperature of the buckets is being improved using updated analysis tools, and a methodology to determine and report the condition of the buckets in real time is being developed.

Task 3 – Advanced Methods for Combustion Process Modeling:
Substantial progress has been made in the development of a combustion dynamics model for control design. The model has demonstrated the ability to accurately predict the primary thermo-acoustic instability exhibited by the single-nozzle combustor to be used in the program for subsequent control system development and testing. Fuel modulation experiments have demonstrated operability improvements in a Dry Low NOx (DLN) combustor including improved lean blowout. Further system identification experiments are underway along with control design.

Task 4 – Information Technology (IT) Integration:
Substantial progress has been made in the development of the GateCycle™ software to model complete-plant IGCC systems (sub-task 4.1), as well as the Universal On-Site Monitor (UOSM) to collect and integrate data from multiple condition monitoring applications at a power plant (sub-tasks 4.2, 4.3).

In order to extend the GateCycle heat-balance software to model complete-plant IGCC systems, the database foundation was reworked so that the IGCC extensions could be added. Several different SQL database design alternatives were explored and tested, with speed of access being the primary issue that needed to be resolved. By focusing on improved stored procedure implementations, a design of a GateCycle SQL database was completed and tested that proved to be acceptably fast for a commercial-grade release. All basic database functionality (except for importing from the previous non-SQL database version) has now been completed and is undergoing final testing and integration. Design has begun of the database changes that will be needed to support the required IGCC modeling extensions, while work continues on improving the database speed and robustness, particularly during program startup.

The UOSM hardware and GE-ICAS2002 condition monitoring system have been installed at the initial MS7001FA+e test site. This system utilizes approximately 50 separate software applications and rules. Synergy software was developed by GE-FANUC to monitor and integrate program anomaly outputs. Several sensor anomalies have been detected and corrected, resulting in improved gas turbine performance and life of the turbine components. The system will continue to be improved and upgraded as new applications and rules are developed.

References

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List of Acronyms and Abbreviations

CTQ – Six Sigma: Critical To Quality
Duke MI – Duke Power Company, Maine Independence Unit
GaTech – Georgia Technology Research Corporation
GEAE – GE Aircraft Engines
GEPS – GE Power Systems
GRC – GE Global Research Center
IGCC – Integrated Gasification Combined Cycle
HGP – Hot Gas Path
IR – InfraRed
IT – Information Technology
LBO – Lean Blow Out
LIBS - Laser Induced Breakdown Spectrometry
LOS – Lin Of Sight
QFD – Six Sigma: Quality Function Deployment
RAM – Reliability, Availability, and Maintainability
SNL – Sandia National Laboratory
SNR – Single Nozzle Rig
TECO – Tampa Electric Company
UOSM – Universal On-Site Monitor